INL/CON-15-36631
PREPRINT

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20th Pacific Basin Nuclear Conference (PBNC 2016)

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April 2016

PBNC 2016
Beijing, China, April 5-9, 2016

A SIMULATION-BASED DYNAMIC APPROACH FOR EXTERNAL FLOODING ANALYSIS IN NUCLEAR POWER PLANTS

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KEYWORDS: EXTERNAL FLOOD, PRA, SIMULATION, DYNAMIC PRA

ABSTRACT: All nuclear power plants must consider external flooding hazards such as local intense precipitation, riverine flooding, flooding due to upstream dam failure, and coastal flooding due to storm surge or tsunami. While external flooding events could potentially interrupt off-site power, threaten plant structures, systems and components important to safety, or limit plant access, they have often been qualitatively assessed as risk insignificant and screened out from detailed evaluation and quantification. Recent lessons learned from the Fukushima seismic/tsunami initiated nuclear accident (2011), the Fort Calhoun (2011), Vermont Yankee (2013), Arkansas Nuclear One (2013), and St. Lucie (2014) flooding events have highlighted the need for more detailed risk analysis. However, developing external flood probabilistic risk assessment (PRA) model using traditional event tree/fault tree approach in static PRA models is challenging because it is difficult to accurately represent plant system and component behavior and reliability of manual actions during an ever-progressing flood event. The plant response to external flood may be highly spatial- and time- dependent, subject to the hydrological and hydraulic characteristics of the flood event. Such unique challenges prompt the investigation of using simulation-based dynamic analysis approaches for external flood risk assessment. Simulation methods can better model the performance of structures, systems, and components during an external flooding event. A general framework to perform a simulation-based dynamic flooding analysis is presented in this paper with the sub-tasks of flood hazard analysis, flood fragility analysis, plant response modeling, safety margin analysis or PRA quantification. A new type of PRA technique, State-based PRA Modeling, is introduced to incorporate time-related interactions such as those from both 3D physical simulations and random failures into traditional PRA logic models.

1. INTRODUCTION

All nuclear power plants must consider external flooding hazards such as local intense precipitation (LIP), riverine flooding, flooding due to upstream dam failure, and coastal flooding due to storm surge or tsunami. While external flooding events could potentially interrupt off-site power, threaten plant structures, systems and components important to safety, or limit plant access, they have often been qualitatively assessed as risk insignificant and screened out from detailed evaluation and quantification. Recent lessons learned from Fort Calhoun (2011), Vermont Yankee (2013), Arkansas Nuclear One (2013), and St. Lucie (2014) flooding events [1-4], as well as the Fukushima nuclear accident (2011) [5], demonstrate that more detailed risk assessment of external flood hazard may be warranted for operating nuclear power plants in U.S. The total plant response must be evaluated to ensure that flood protection features and procedures as well as flood mitigation measures are adequate to ensure plant safety.

There are many unique challenges in modeling the complete plant response to the flooding event. Structures, systems, components (SSCs), flood protection features, and flood mitigation measures to external flood may be highly spatial- and time-dependent and subject to the hydrometeorological, hydrological and hydraulic characteristics of the flood event (e.g., antecedent soil moisture, precipitation duration and rate, infiltration rate, surface water flow velocities, inundation levels and duration, hydrostatic and hydrodynamic forces, debris impact forces, etc.). Traditional event tree/fault tree approach as in a static probabilistic risk assessment (PRA) model may be inadequate to address these unique challenges and accurately represent plant system and component behavior and reliability of manual actions during an ever-progressing flood event. Simulation-based methods and dynamic analysis approaches are believed to be able to better model the performance of structures, systems, components, and operator actions during an external flooding event. In support of the Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment (PFHA) Research Plan [6, 7], Idaho National Laboratory (INL) is tasked to develop such new approaches and demonstrate a proof-of-concept for the advanced representation of external flooding analysis. A series of case studies are envisioned to demonstrate the basic feasibility and to work out technical issues. This paper presents a general framework to perform a simulation-based dynamic flooding analysis (SBD-FA) with the tasks of flood hazard analysis, flood fragility analysis, plant response modeling, safety margin analysis or PRA quantification. A new type of PRA technique, State-based PRA Modeling, is introduced to incorporate time-related interactions such as those from both 3D time-dependent physical simulations and random failures into traditional PRA logic models.

2. FRAMEWORK OF SIMULATION-BASED DYNAMIC FLOODING ANALYSIS

Performing external flood analysis is a core piece in the risk-informed decision making process for external flood-related events. With the hazard problem being understood and defined, the external flooding event is evaluated using the SBD-FA. After the verification and validation of the analysis, the results can be used to provide valuable risk insights to the decision makers. This general process is illustrated in Figure 1.

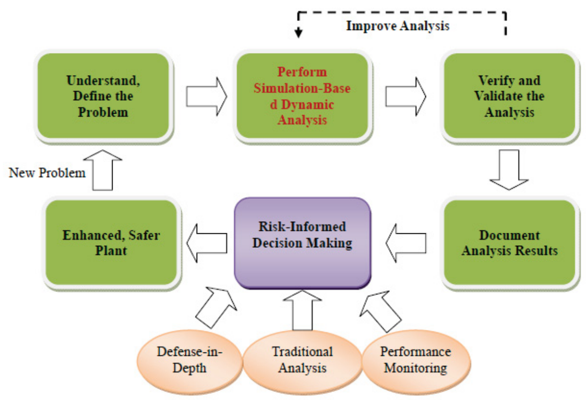

Fig. 1. Simulation-based dynamic analysis in risk-informed decision making process.

Figure 2 (attached at the end of this paper) presents the general framework to perform a SBD-FA. There are four main tasks under this framework to perform an external flooding margins type analysis or PRA: (1) flood hazard analysis; (2) flood fragility analysis; (3) plant response modeling; and (4) 3D simulations for safety margin or PRA quantification. Tasks 1 and 2 are only briefly described here while Tasks 3 and 4 are further discussed in later sections.

2.1 Perform External Flood Hazard Analysis

This task evaluates the frequency of occurrence of external floods as a function of severity based on recent information and up-to-date databases, or by using simulation of the flood-causing mechanism (e.g., precipitation model and rainfall-runoff model. The output of this task is a hazard curve (or a family of hazard curves) giving occurrence frequency versus hazard intensity. Uncertainties in the parameter values and in the mathematical model of the hazard should be properly accounted for and propagated to obtain a family of hazard curves including a mean hazard curve. A probability distribution is assigned to the family of curves to represent the relative likelihood of one hazard curve relative to the others.

The hazard analysis should identify all of the external flood mechanisms (including combinations of mechanisms) that are applicable to the site. A non-inclusive list that is categorized under the external flood hazard analysis includes: local intense precipitation, river and stream flooding, dam and levee failure, tsunami, hurricane, waves, storm surge, seiche, high tide, snow, and coastal erosion. For each flood mechanism, the hazard intensity as well as other flood parameters such as water height, event duration, plant modes, and plant accessibilities need to be evaluated. Multiple sets of flood scenario parameters or one set of bounding flood scenario parameters are developed for later plant response analysis.

Instead of using the mean value as the initiating event frequency in traditional flood analysis, the full spectrum of the flood hazard curves, as well as other hydrological and hydraulic characteristics such as the precipitation rate and flow rate, could be assessed in the SBD-FA.

2.2 Perform External Flood Fragility Analysis

This task evaluates the fragility of plant SSCs as a function of the severity of the external flood using an engineering method for the postulated failure. The output of this task is a table of SSCs that are evaluated in the plant response model, as well as their failure probabilities as a function of the severity of the external floods (e.g., fragility curves, fragility tables, or failure models based upon flooding characteristics).

Unlike the concept of critical flood height used in traditional flooding analysis, the SSC fragilities could be associated with various flood heights and various inundation rates in a SBD-FA, i.e., different SSC failure probabilities for different inundation levels and different flow rates.

2.3 Develop External Flood Plant Response Model

This task develops a plant response model that addressed the initiating events and the failures caused by the effects of external flooding that can lead to core damage or large early release. The model reflects external flood-caused failures as well as other unavailability and human errors that give rise to significant accident sequences or significant accident progression sequences. A new type of PRA technique, State-based PRA Modeling, is applied in this task in order to incorporate time-related interactions from both 3D physical simulations and random failures into traditional PRA logic models.

2.4 Perform 3D Simulations for Safety Margin Analysis or PRA Quantification

This task will perform 3D simulations for safety margin analysis or PRA quantification by incorporating simulation-based methods and probabilistic and mechanistic calculations to represent the flooding scenarios and construct probabilistic load and capacity curves for relevant plant features.

3. PLANT RESPONSE MODEL

The plant response modeling task develops a plant response model that includes external flood-induced initiating events and other failures, non-external flood induced unavailabilities (such as random failures, unavailabilities due to test or maintenance), and human errors associated with plant flood response that can cause significant accident sequences or significant accident progression sequences. The plant response model starts from the occurrence of an external flood initiating event (for example, a LIP event with precipitation rate of x inch per hour, or a dam failure with a discharge of x cubic feet per second at the site), identifies the SSCs and human actions that participate in plant responses to the flood and thus accident sequences, examines the adverse impacts caused by the external flooding which include external flood-induced initiating events (for example, a general transient that shuts down the plant, a loss of offsite power, or a loss of service water) and other failures, and assesses accident sequences based on the plant configurations and responses including the plant flood protection features and flood mitigation measures, the external flood-induced initiating events, other external flood-induced failures, and non-external flood-induced failures.

As shown in Figure 3, total plant responses to an external flood event can be divided into two stages: external plant response (EPR) stage and internal plant response (IPR) stage. During the EPR stage, the plant flood protection features, including both as-designed features (e.g., site drain system, water-tight doors and penetration seals, drain systems within buildings, etc.) and temporary features (e.g., portable pumps, sandbag barriers, etc.), perform their functions and prevent risk important SSCs from flood damages. If the flood protection features fail to perform the functions and the manual actions (e.g., installation of portable pumps and floodgates, construction of barriers) are not effective, the plant would be in undesirable conditions of flood damage state (FDS) with the external flood-induced initiating event and other risk important SSC failures. The plant response

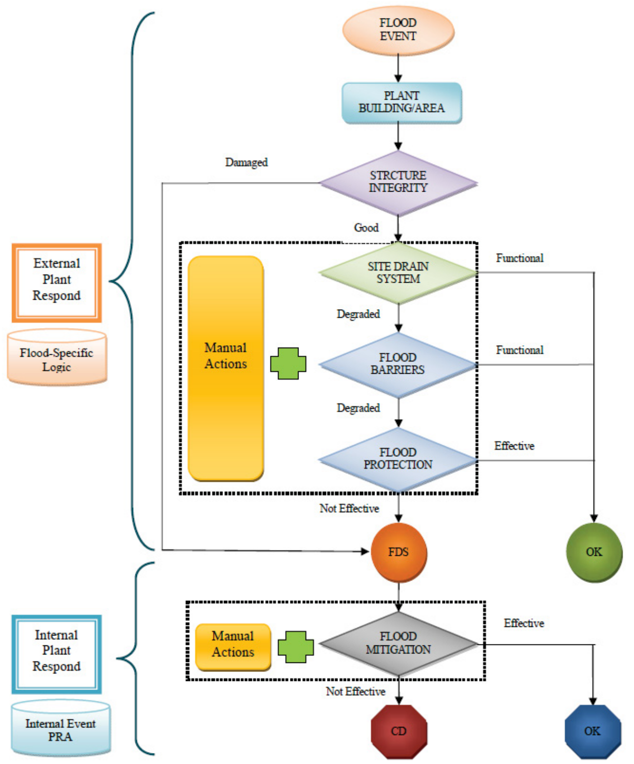

Fig. 3. Total plant response to external flood.

enters the next stage, IPR stage, which would evaluate plant mitigation measures along with the manual actions to maintain key safety functions and prevent core damage and large early release. While an internal event, at-power PRA model usually exists prior to the external flood analysis, and can be used as the basis, modified as appropriate, to model the IPR stage for key safety functions and core damage frequency (CDF)/large early release frequency (LERF) analysis, the EPR stage modeling may involve new, flood mechanism-specific analysis for the site.

However, incorporating an external flood model into the traditional event tree/fault tree approach used in static probabilistic risk assessment (PRA) models is challenging because it is difficult to accurately represent plant system and component behavior and reliability of manual actions during an ever-progressing flood event. A new type of PRA technique, State-based PRA Modeling, would address such difficulties by integrating simulation and time elements into the logic models. Advanced 3D modeling and simulations are conducted in the new technique. Simulation methods can better illustrate the SSCs performance and their responses along with the flooding event progresses. 3D physical simulations, Monte Carlo simulations of components, and mechanistic analysis are coupled together to represent the flooding event and determine which SSCs fail, when they fail, what caused their failure, what impact these failures have on associated systems, and what impact system failures have on the overall plant. The state-based PRA model uses "states" to represent and track the conditions of the SSCs in the model. A set of states is represented at any given moment within the mission time. The set of current states could change over the time until a terminal state is reached. The state-based PRA model could be developed from scratch or converted from an existing traditional PRA model. A new tool, EMRALD (Event Model Risk Assessment using Linked Diagrams), is being developed to support the state-based PRA modeling technique.

4. NEW STATE-BASED PRA MODELING TECHNIQUE

A state-based PRA model uses "states" to represent and simulate time based plant responsive behaviors and dependencies. Except several special state types, each standard state is a logical representation for the condition of a component, system, or human event. Special types of state include *Start State* that is to be included in the current state list, *Key State* that is to be tracked for final probability calculations (corresponding to the "End State" in traditional PRA model), and *Terminal State* that will terminate the simulation runs of the model. Each state has two attributes: Actions and Events. The Actions attribute depicts what the model will act after entering the state. There are three types of Actions: *Transition* which will start or move to another state or states, *Change Value* which can change the value of a variable, and *3D Sim Action* which send a message to the 3D simulator. The Events attribute will trigger an action or set of actions when the defined condition is met. There are six types of Events: *Timer* which executes when time has passed, *Failure Rate* which executes when the sampled time based on the "random" failure rate has passed, *State Change* which executes when the associated state is included in the list of current states, *Component Logic* which execute when the defined logic for set of components (or a system) is met, *Variable Condition* which executes if a variable meets the user defined condition, and *3D Simulation* which executes if the related component fails in the 3D simulation. The model is in a set of states at any given moment in time. The rest of this section will describe how the components, system logics, and accident sequence be modeled in a state-based PRA.

4.1 Component Modeling

The condition of a component is usually defined by a group of states such as *Standby*, *On*, and *Failed*. The transition from one state to another state is determined by the Events of the initial state. Figure 4 displays an example of a state group diagram. Component E-PUMP-B is represented by three states in the group. "[*,1] E-PUMP-B_*Standby*" is the start state of the component. When simulation starts, the *Standby* state will transit to "[1] E-PUMP-B_*On*" if the pump starts successfully, or transit to "[0] E-PUMP-B_*Failed*" if the pump fails to start. Whether transit to the *On* state or to the *Failed* state is determined through Monte Carlo simulation with the pump fail-to-start probability. If the pump starts successfully and enters the *On* state, it will either run successfully through the mission time and end with a success flag, "[1]", for the component, or fail to run due to the random failure through the Monte Carlo simulation with the fail-to-run probability, or fail to run due to the flood-caused failure through the 3D simulation. Both Fails_To_Run and 3D_Sim_Flooded events will transfer to the *Failed* state. The *Failed* state will stop E-PUMP-B with a failure flag, "[0]" for the component. Flood protection features such as flood barriers could be modeled in a similar way with their failure probabilities estimated in Task 2 External Flood Fragility Analysis.

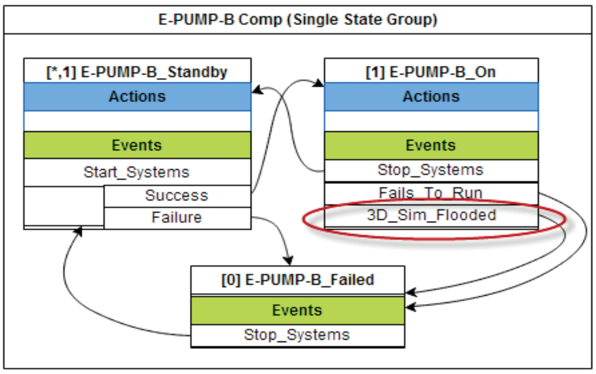

Fig. 4. Example of component state group diagram.

4.2 System Logic Modeling

The status of a system is also defined by a group of states such as *Active* and *Failed*. The right side of Figure 5 shows the state group diagram for CCS System. The "[1] CCS_Sys_*Active*" state (right side of Figure 5) will evaluate the CCS fault tree (FT) in the model. The system FT is similar to the one in traditional PRA model that depicts the system logic and evaluates the system top's success or failure (left side of Figure 5). However, unlike the traditional FT that has both the component and the failure modes as the basic events, the system FT in a State-based PRA uses only the component as the basic events since the failure modes such as fail-to-start and fail-to-run are already embedded in the associated component states.

After all component states in a system are modeled and evaluated through the Monte Carlo simulations and/or 3D simulations, the system logic will be evaluated and the results (system success or failure) are returned to the plant model.

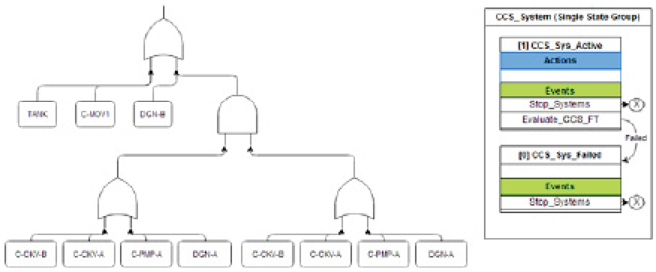

Fig. 5. Example of system state diagram and system logic.

4.3 Accident Sequence Modeling

There is no explicit tool, such as the event tree (ET) in a traditional PRA model, to show the accident sequences in a state-based PRA model. The accident sequences are rather implicitly represented in the plant state diagram with the flow paths between the start state, initiating event states, system/component states, and key/end states. As a simple example, the flow paths in Figure 6 imply two event trees, LOSP and Tsunami. Each event tree has two accident sequences. The first one is with the occurrence of the initiating event (IE) (either LOSP or Tsunami), ECS system

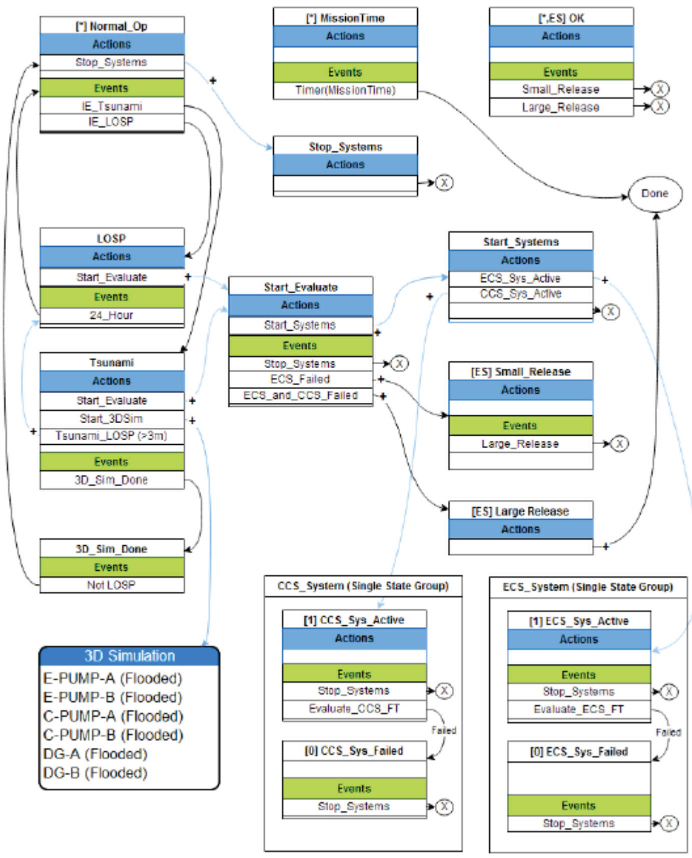

Fig. 6. Example of plant state diagram.

fails and cause small release. The second one is with the occurrence of the IE, both ECS and CCS systems fail which leads to large release.

One can see from the example in Figure 6 that other than the standard component/system states introduced in above sections, a plant state diagram would also include other special states such as the *Normal_Op* state as the starting state for the simulation, the *LOSP* and *Tsunami* states as the initiating event states, the *MissionTime* state that serves as the timer and finishes the simulation after the mission time has elapsed, the *Small_Release* and *Large_Release* states as the key states (or end states), and the *Start_Systems* and *Stop_Systems* states that start or stop to evaluate systems or components.

5. 3D SIMULATIONS FOR SAFETY MARGIN AND PRA ANALYSIS

This task performs safety margin analysis by incorporating 3D flood simulations into state-based PRA model to represent the flooding scenarios and the plant response progress. In this project, a 3D site terrain model can be obtained for the interested plant with a web-based application that interacts with the Google's Elevation API. A 3D plant model can be developed with available plant information such as layout drawings. Then, flooding scenarios and pathways in a flooding event are identified. 3D simulation models are developed to simulate the flooding scenarios and communicate with the state-based PRA model. The factors and controls that determine safety margin are identified and characterized by coupling the PRA model with the Risk Informed Safety Margin Characterization (RISMC) toolkit [8].

5.1 3D Site Terrain Model

To simulate the evolution of an external flooding event, a terrain map with the topography of the site area is needed. In this project, a web-based application, Web Terrain Mapper API, was used to obtain such information using the public available Google's Elevation API which retrieves elevation levels from a set of points in a rectangular area anywhere on the surface of the earth. After the position and size of the site area, as well as the resolution data, are input, the application provides a visual representation of the defined area on a Google map and output the terrain map as a 3D model.

5.2 3D Plant Model

To simulate the progression of a flooding event, a 3D plant model must be developed using available plant information such as layout drawings. The level of details for the 3D plant model could be varying as long as they are sufficient for the flooding scenarios to be simulated.

5.3 3D Simulation Model

3D simulation software Neutrino has been used in previous INL projects [9-11] and is used in this project for LIP simulations. Neutrino can handle the memory requirements needed for large simulations while provide accurate fluid movement. Its fluid solver is based on Smooth Particle Hydrodynamics (SPH) [12-14] with a pressure solver to handle incompressible fluids. The fluid solver factors in accurate boundary handling and adaptive time stepping to help to increase accuracy and calculation speed. Neutrino provides a variety of tools to measure parameters in a section of the fluid simulated, including flood height at a specific point, average pressure and average velocity in a certain area or volume, and flow rate across a certain area or volume.

3D simulation models combine the 3D terrain model and 3D plant models developed in previous steps. Figure 7 shows an example of 3D simulation model and a screen shot of one flooding scenario that was simulated using Neutrino [9] for the project.

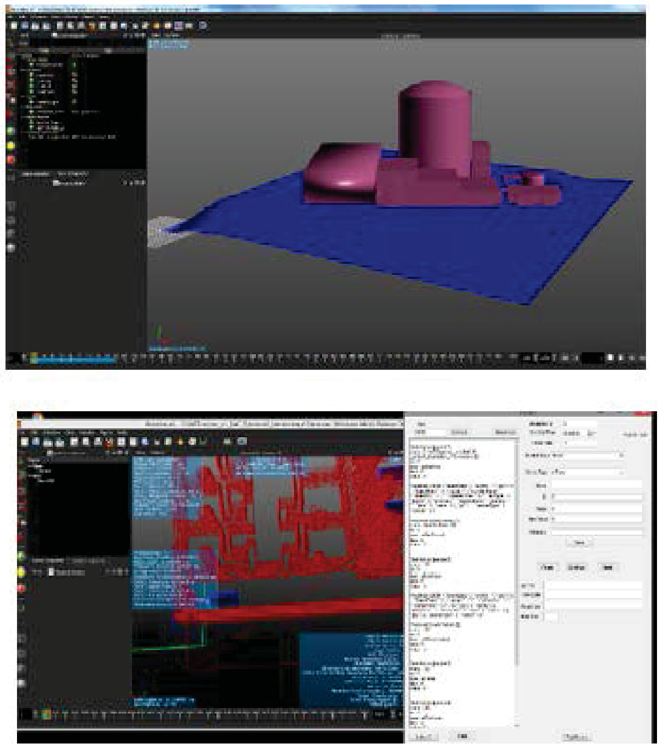

Fig. 7. 3D simulation model.

5.4 Perform Safety Margin or PRA Quantification

To perform safety margin or PRA quantification with simulations, the state-based PRA model must incorporate 3D simulation elements (flood initiating event, flood-caused failure events, and simulation related state/event) into the logic. The state-based PRA model can call to start the 3D flood simulation and monitor the component status from both the random failure side and the flood-caused failure side. When a monitored component fails in 3D flood simulation, the change of status is fed back to the state-based PRA model and the component state is flagged with failure due to flood. The state-based PRA model can then be quantified with the system logics and accident sequences embedded in the model.

With the workable 3D simulation models and state-based PRA model, the factors and controls that determine safety margin are identified and characterized. SSCs robustness is assessed through quantified margins. The defense-in-depth capabilities can be evaluated [11]. Necessary simulations are performed on the models to measure plant responses for various hazard parameters and different values. The plant response function can be built and implemented in thermal hydraulic codes to evaluate the impact of external flood hazards on the plant.

6. CONCLUSIONS

All nuclear power plants must consider and evaluate external flooding risks such as local intense precipitation, dam failure, and coastal flooding due to storm surge or tsunami as they could challenge off-site power and other plant structure integrity, threaten plant safety systems and components, and limit plant access. Lessons learned from recent flooding events in U.S. as well as the Fukushima accident reveal that more detailed risk assessment of external flood hazard is warranted for safe operation of nuclear power plants. However, developing an external flood model with traditional event tree/fault tree approach could be a challenge as the plant response to flood may be highly spatial- and time- dependent and subject to the hydrological and hydraulic characteristics of the flood event. This paper presents a general framework to perform a simulation-based dynamic flooding analysis (SBD-FA) with the tasks of flood hazard analysis, flood fragility analysis, plant response modeling, safety margin analysis or PRA quantification. The paper describes in details on how to develop plant response model by introducing a new type of PRA technique (i.e., State-based PRA Modeling), as well as the process to perform safety margin or PRA analysis with advanced 3D simulation capabilities. With the State-based PRA Modeling and 3D simulation, the SBD-FA incorporates time-related interactions from both 3D physical simulations and random failures into traditional PRA logic models. The SBD-FA also applies Monte-Carlo simulations for initiating event frequencies and basic event failure probabilities in the model. The successful applications of the SBD-FA in previous and current projects demonstrate that this simulation-based dynamic approach is promising for external flood analysis.

ACKNOWLEDGMENTS

This work was supported by the U.S. Nuclear Regulatory Commission. We appreciate the insights and reviews provided by Joseph Kanney and Fernando Ferrante at NRC, as well the support from Ram Sampath at Centroid PIC.

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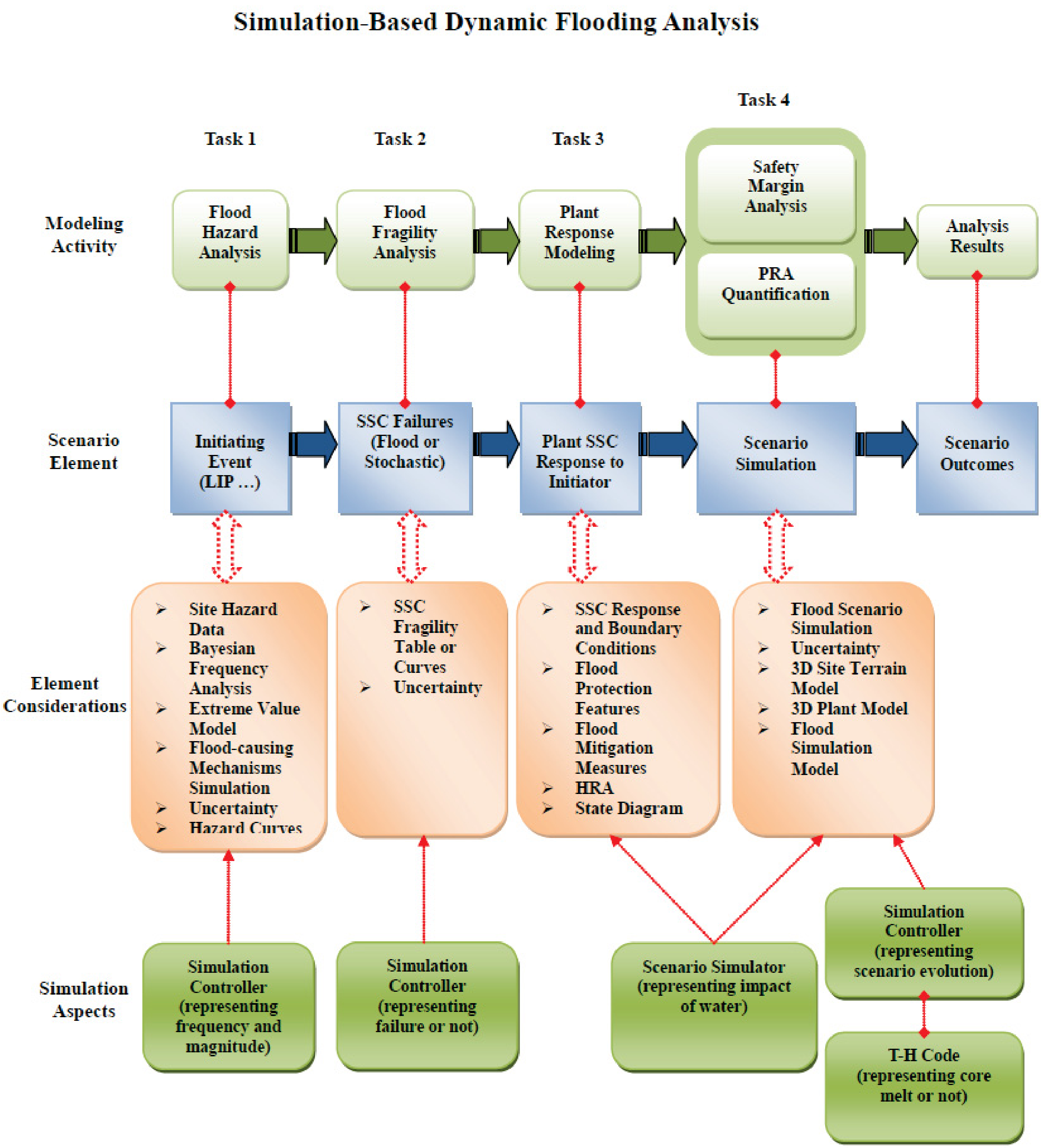

Fig. 2. Simulation-based dynamic flooding analysis (SBD-FA) framework.